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# Tokamak power exhaust with the snowflake divertor: present results and outstanding issues.

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**Abstract** A snowflake divertor magnetic configuration (D.D. Ryutov, Phys. Plasmas, 14, 064502, 2007) with the second-order poloidal field null offers a number of possible advantages for tokamak plasma heat and particle exhaust in comparison with the standard poloidal divertor with the first-order null. Results from snowflake divertor experiments are briefly reviewed and future directions for research in this area are outlined.

**Keywords** Divertor · Tokamak · Plasma power exhaust

**PACS** PACS code1 · PACS code2 · more

**Mathematics Subject Classification (2000)** MSC code1 · MSC code2 · more

## 1 Introduction

The present vision for controlling the plasma-material interface of a tokamak is an axisymmetric poloidal X-point divertor. The divertor must enable access to high core and pedestal plasma performance metrics while keeping target plate heat loads and erosion within the operating limits of plasma-facing component cooling technology and target plate materials. The ITER divertor design is based on standard X-point geometry designs tested in large tokamak experiments and optimized via modeling. It uses tilted vertical targets to generate partial radiative detachment of the strike points [1,2]. However, the standard poloidal divertor approach is likely to be insufficient for next step advanced tokamak and spherical tokamak devices such as the proposed fusion nuclear science facilities and for the DEMO reactor.

## 2 Snowflake divertor: status and issues

The history of the poloidal divertor development shows many examples of the concept optimization based on tokamak magnetic geometry and plasma-facing component geometry

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[3]. A snowflake divertor [4–6] is based on the magnetic configuration where a second-order poloidal field null is created by bringing two first-order null-points together or close to each other, thereby producing a larger region of lower poloidal field in the divertor (cf. standard divertor). Poloidal magnetic flux surfaces in the region of the second-order null have hexagonal separatrix branches with an appearance of a snowflake. Initial experiments in several tokamaks (TCV [7], NSTX [8], DIII-D [9, 10], and EAST [11]) provide increasing support for the snowflake configuration as a viable tokamak heat exhaust concept. This paper summarizes the snowflake properties predicted theoretically and studied experimentally, and identifies outstanding issues to be resolved in existing and future facilities before the snowflake divertor can qualify as the reactor power and particle exhaust interface.

*Magnetic configurations and equilibria development* The snowflake configuration has been created on several tokamaks without any changes to existing poloidal field coil sets. Equilibria designs are performed using free boundary Grad-Shafranov equilibria codes. The optimization of the poloidal field coil number and layout that involves coil placement outside of the toroidal field coil has been demonstrated [12, 13]. Further work is necessary for specific plasma shaping parameters for existing and future tokamak designs.

*Real-time feedback control* Initial experiments used off-line equilibria designs and pre-programmed poloidal field coil currents, with the exception of recent DIII-D control studies [14]. Additional developments of real-time magnetic diagnostics, null-tracking algorithms, and multi-input multi-output control schemes is required to address long-pulse discharge control.

*Impact on core and pedestal* Initial experiments generally show no detrimental snowflake divertor effects on core confinement [7, 8, 10]. The pedestal structure and ELM properties (energy and frequency) are apparently affected, suggesting that MHD stability is modified due to higher edge magnetic shear and modified plasma pressure gradient [7, 10, 15–18]. Additional experiments and analysis on existing facilities are needed to obtain a systematic assessment of these effects, including clarification of the plasma shaping variations. Increased prompt ion loss through the second-order null region is predicted theoretically [19] and may affect the edge electric field and velocity shear.

*Heat and particle flux sharing among all divertor legs* This unique snowflake divertor property was observed experimentally [18, 20–22] and is highly beneficial for inter-ELM and ELM peak heat flux mitigation. The associated transport mechanism is not well understood and can include particle drifts [23], flute-like and ballooning instabilities leading to fast convection [24–29], and magnetic field stochasticization. Additional measurements (e.g., divertor density fluctuations, divertor plasma pressure profiles, and divertor plasma flow) are needed for divertor transport and turbulence studies. Identification and development of a multi-device scaling of the heat flux sharing effect is desirable.

*Improved divertor geometry properties* The increased magnetic flux expansion in the vicinity of the main strike points, and the increased connection length in the scrape-off layer have been demonstrated experimentally [9, 16, 20]. Anticipated effects on the divertor plasma include increased radial transport and temperature drop in each divertor leg, a longer divertor particle residence time, disconnection of turbulence along the flux tube due to stronger shearing in the snowflake region, and increased flux tube volume and radiation. Some of these

effects have been observed and characterized through modelling [22, 30, 31]. Additional experiments and modeling are needed to systematically investigate divertor heat and particle (impurity) transport as functions of geometry properties and plasma collisionality (e.g. in a transition from low-recycling to high recycling and detached).

*Radiative snowflake divertor and detachment* Initial radiative snowflake experiments used deuterium seeding and intrinsic carbon impurities, or additional impurity seeding ( $\text{CD}_4$  in NSTX, neon in DIII-D and TCV), and demonstrated additional peak heat flux reduction, including peak ELM heat fluxes, nearly full power detachment, and increased divertor radiation, in some cases with a modest degradation in core confinement [16, 32–35]. Experiments in existing facilities with upgraded diagnostics should clarify the impurity radiation distribution in the snowflake divertor, dynamics of radiative condensation instability formation and threshold, impurity screening, and compatibility with particle control techniques (e.g., cryopump).

*3D fields* Combining the snowflake divertor with applied three dimensional magnetic fields for MHD and ELM control can be studied in existing facilities and could provide interesting potentially synergistic effects for the reactor.

*Near-term direction* Existing facilities in the US (Alcator C-Mod, DIII-D and NSTX-U tokamaks) can support many of the snowflake development efforts with existing and upgraded diagnostic and facility capabilities. Snowflake divertor studies would also greatly benefit from international collaborations with the HL-2M [36] and EAST tokamaks in China, and TCV and MAST-Upgrade [37, 38] tokamaks in Europe, where snowflake divertor studies are planned in the near future. The ultimate goal of this research is the physics basis for the snowflake divertor in a tokamak fusion reactor.

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